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Mass.) 43 p HC A03/MF A01 CSCL 10A

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DESIGN AND FABRICATION OF SOLAR CELL MODULES

"THE JPL LOW-COST SILICON SOLAR
ARRAY PROJECT IS SPONSORED BY
THE U.S. DEPARTMENT OF ENERGY AND
FORMS PART OF THE SOLAR PHOTO-
VOLTAIC CONVERSION PROGRAM TO
INITIATE A MAJOR EFFORT TOWARD THE
DEVELOPMENT OF LOW-COST SOLAR
ARRAYS. THIS WORK WAS PERFORMED
FOR THE JET PROPULSION LABORATORY,
CALIFORNIA INSTITUTE OF TECHNOLOGY
BY AGREEMENT BETWEEN NASA AND DOE."

FINAL TECHNICAL REPORT

CONTRACT NUMBER 954655

SUBMITTED TO:
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CA 91130



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FR-77-10048
April 1978

DESIGN AND FABRICATION OF
SOLAR CELL MODULES

Final Technical Report

Contract Number 954655

Submitted to

Jet Propulsion Laboratory
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, CA 91103

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SECTION I

INTRODUCTION

This report describes a six month program conducted between December 1976, and May 1977, for design, fabrication and evaluation of twelve silicon solar cell modules. The purpose of the program has been to develop a module design consistent with the requirements and objectives of JPL Specification 5-342-1, Revision B, but also incorporating elements of new technologies under development to meet LSSA Project goals.

Module development emphasized preparation of a technically and economically competitive design based upon utilization of ion implanted solar cells and a glass encapsulation system. Ion implanted cells and glass encapsulation methods are expected to have important roles in the reduction of terrestrial solar array costs. This program presented opportunity for initial examination of special considerations which may be associated with these approaches.

The modules fabricated, tested and delivered to JPL were of nominal 2 X 2 foot dimensions and 20 watt minimum rating. Basic design, design rationale, performance and results of environmental testing are described.

SECTION II

MODULE DESIGN

2.1 GENERAL

Figure 1 shows the 12 modules fabricated as items deliverable to JPL. A single module is shown in Figure 2. Each module consists of 48, 3-inch diameter, ion implanted junction cells connected in series and laminated between two sheets of common window glass. The glass sheets are mechanically clamped to a frame constructed of extruded aluminum rectangular tubing. The cavity between the two glass sheets is filled with Dow Corning Q3-6527 Silicone Dielectric Gel.

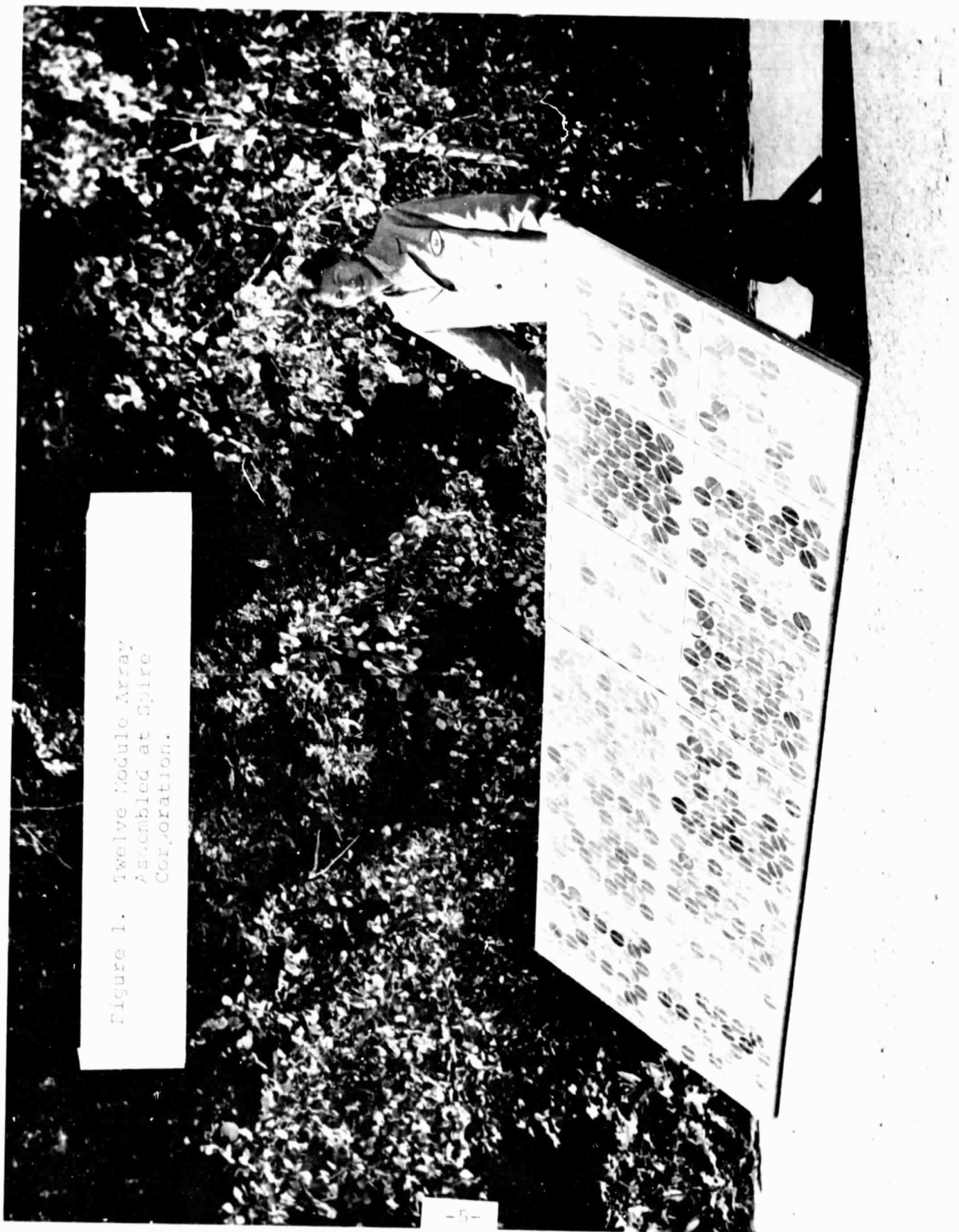
2.2 SOLAR CELL PROCESSING

Both the material and the process sequence chosen for cell fabrication were selected not for maximum achievable performance, but rather for good performance from industry standard material and brief, simple processing procedures yielding reproducible results. The cells were made from nominal three inch diameter, "solar grade", p-type silicon wafers. These wafers are relatively inexpensive due to variations in resistivity and diameter and their "as-cut" surface condition.

An acid etch was used to improve the wafer surface. Cell junctions were introduced by ion implanting p^{31+} followed by a furnace anneal of the ion implant damage. Cell metalization was accomplished by evaporation of titanium silver through a mask, plating silver for increased thickness, and adding a solder layer over the cell's center buss bar. The antireflection coating was TiO_2 . The process sequence for cell fabrication is summarized in Table 1.

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Figure 1. Twelve Module Array
Assembled at Spire
Corporation.



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Figure 2. Configuration of 48 Cell Module.

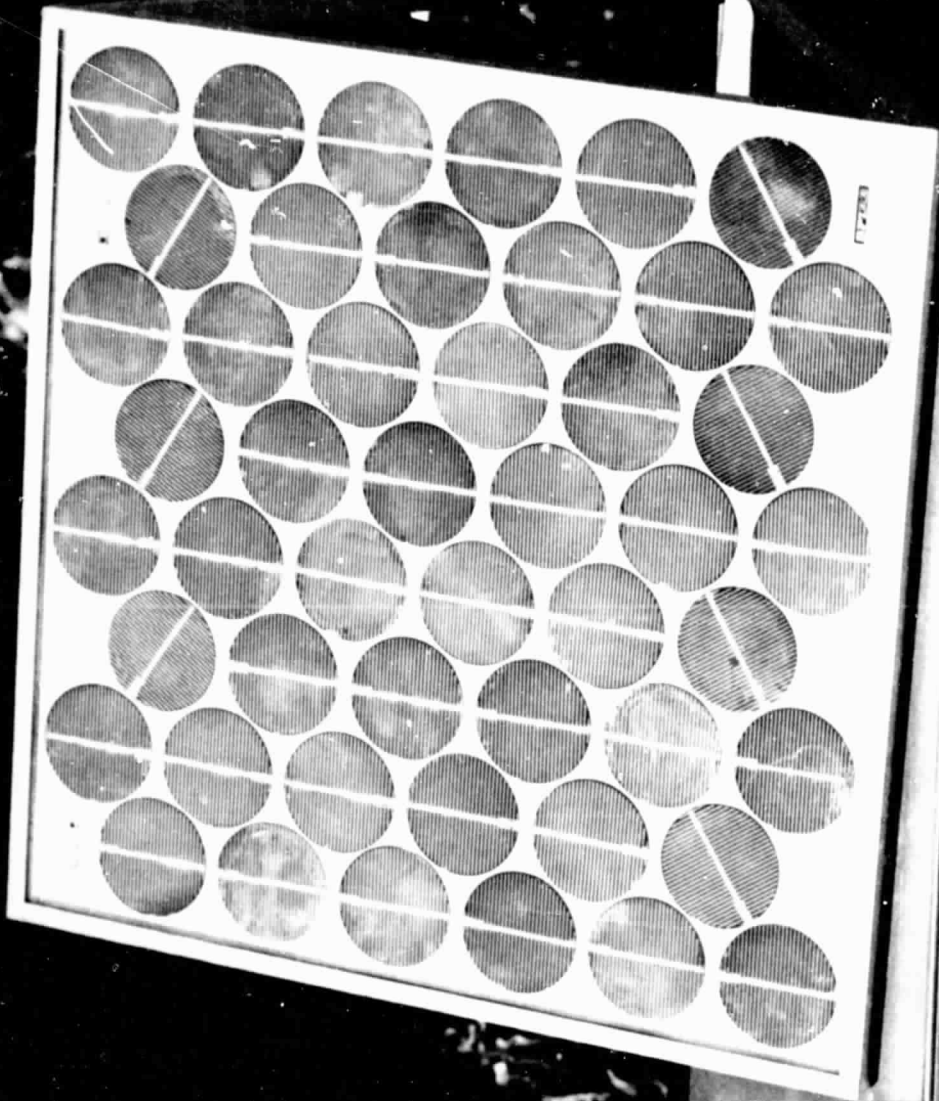


Table I

PROCESS SEQUENCE FOR FABRICATION OF
ION IMPLANTED N^+ / PP^+ SOLAR CELLS

1. Acid etch.
2. Ion Implant Junction.
3. Anneal Implantation Damage.
4. Evaporate Aluminum on Back Surface.
5. Alloy Aluminum.
6. HF Flush and Clean.
7. Vacuum Evaporate Front Contact TiAg.
8. Vacuum Evaporate Back Contact TiAg.
9. Sinter.
10. Electroplate Silver on Front Contact.
11. Sinter.
12. Vacuum Evaporate TiO_2 AR Coating.

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The I-V characteristics of a typical module cell under simulated AMO illumination are shown in Figure 3, as a function of cell temperature. At 20°C the characteristics of this particular cell are a short circuit current of 1240 mA, an open circuit voltage of 580 mV and a fill factor of 0.73.

2.3 ENCAPSULATION SYSTEM

Glass is a promising candidate for encapsulation of solar cell arrays. Not only can glass meet the 1985 cost goals, it is an excellent environmental barrier, offers resistance to darkening, has high thermal emissivity, has good optical transmission, is easy to clean and shows resistance to pitting and general durability.

The modules have sheets of glass as the primary encapsulant. These sheets, placed above and below the cell array, are separated by a silicone rubber gasket. The resulting cavity is filled with Dow Corning Q3-6527 Silicone Dielectric Gel. In its cured form, this gel has relatively low viscosity so that the cells and interconnects are not rigidly clamped to the glass or support structure but float, adjusting for thermal expansion coefficient mismatch. This mechanical decoupling allows low cost standard soda-lime window glass to be used.

In addition to providing thermal stress relief, dielectric gel has other attractive characteristics. Once cured, the transparent material provides a cushioning, resilient environment for the interconnected cells which is retained over a wide range of temperature. Mechanical stress, strain or shock coupled to the cells and interconnects is minimized by transmission through the gel. No

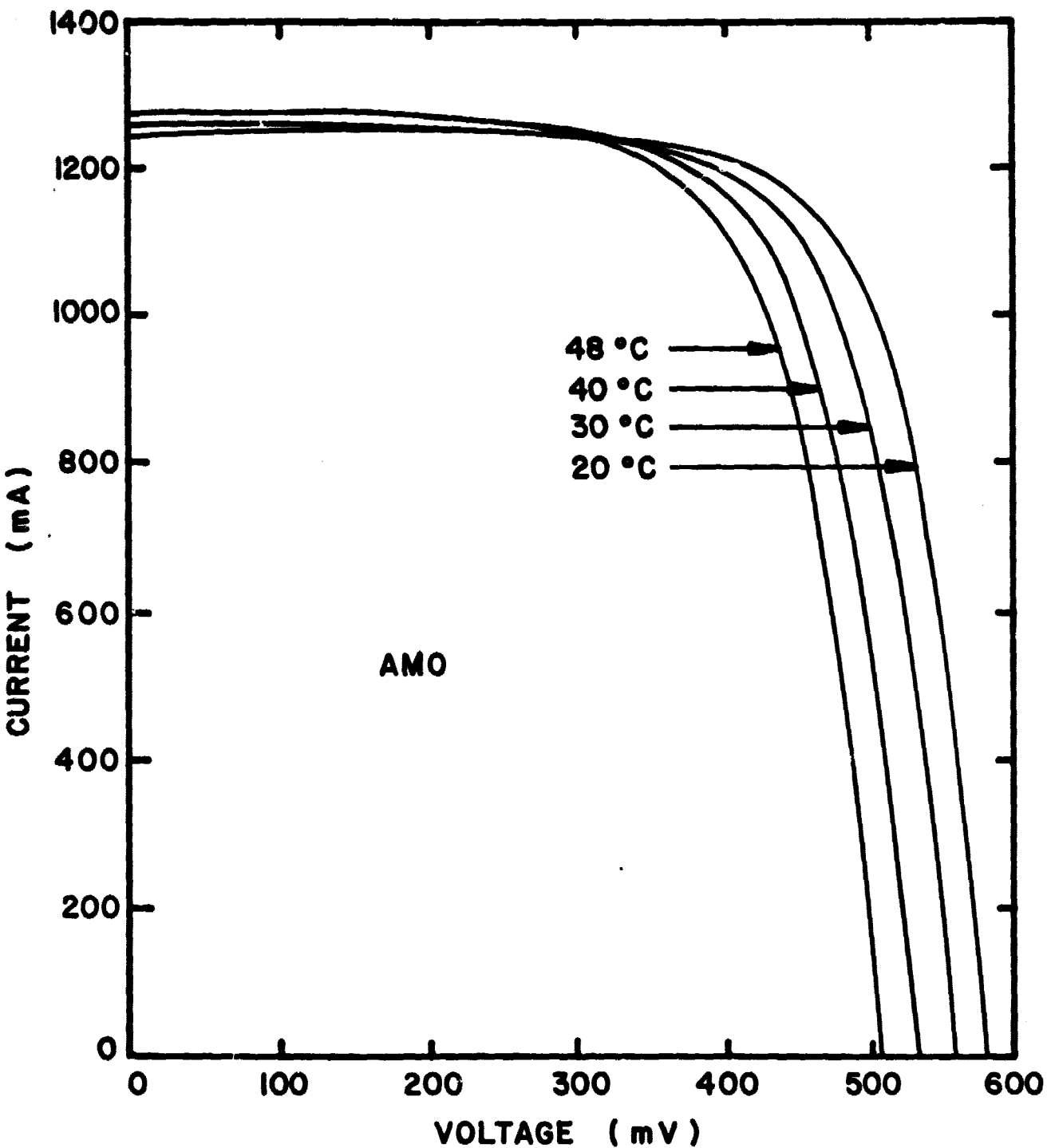


Figure 3. AMO I-V Characteristics of Typical Implanted Cells as a Function of Temperature

primer is required to achieve a permanent, pressure-sensitive adhesion. Cured gel is hydrophobic, that is it repels water, thereby providing substantial second line protection against moisture which may have penetrated the gasket seal. Finally, the use of airless metering and dispensing equipment permits relatively routine, bubble free gel filling.

The material and configuration chosen for the module gasket received considerable attention due to the appearance of air bubbles in the dielectric gel, near the module frame, after thermal cycling. Figure 4 shows a representative bubble formation structure, which results from the large thermal expansion coefficient of the gel drawing air through the gasket during cooling. Therefore, three different gasket design configurations were evaluated. Figure 5 shows these schematically. Type A was the initial design which revealed the bubble formation defect. Gasket types B and C attempted to provide a gel reservoir for volume changes. All three types were formed with clamped, compressed, dry silicone rubber. Although some retardation was accomplished with the latter designs, all subsequently showed bubble formation.

2.4 STRUCTURAL ASSEMBLY

The major elements of the structural design of the module are shown in Figure 6. A frame made from extruded aluminum tubing of square cross section provides the principle support. The glass/gel/solar cell/gel/glass laminate is placed upon this frame, protected with silicone rubber gaskets, and clamped into position with an "L" shaped aluminum bracket pop-riveted to the lower frame.

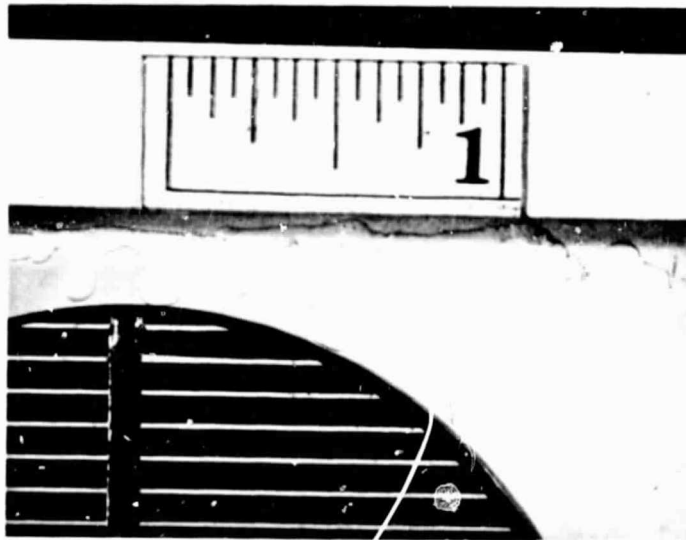
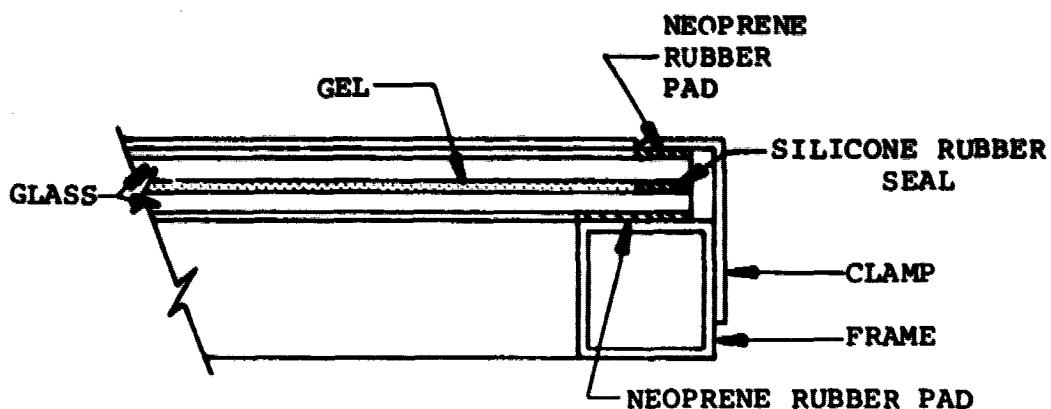
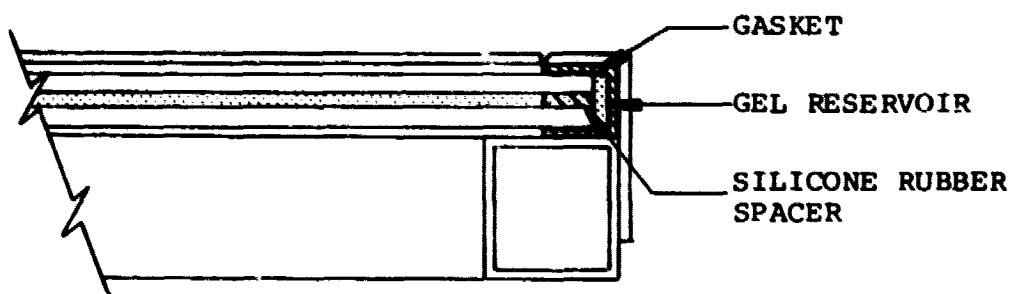


Figure 4. Bubble Formation Near Module
Frame in Silicone Gel Encapsulant
After Temperature Cycling.

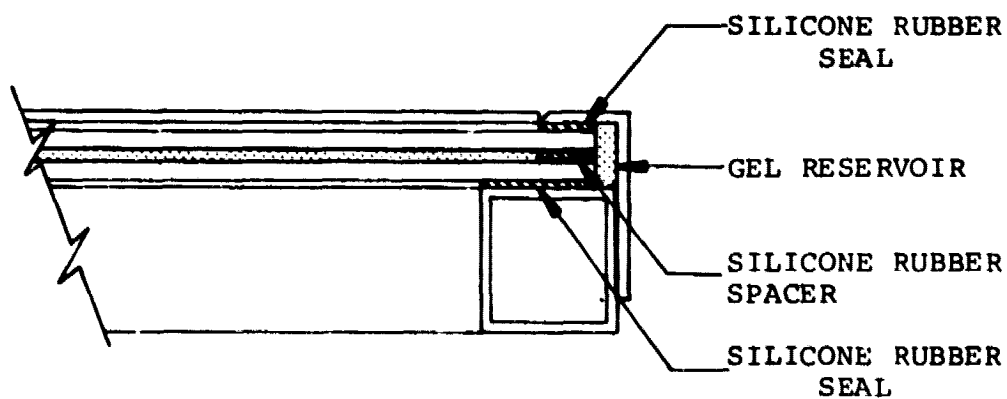
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TYPE A



TYPE B



TYPE C

Figure 5. Gasket Configurations Evaluated During Module Development. Type B Results in Best Performance.

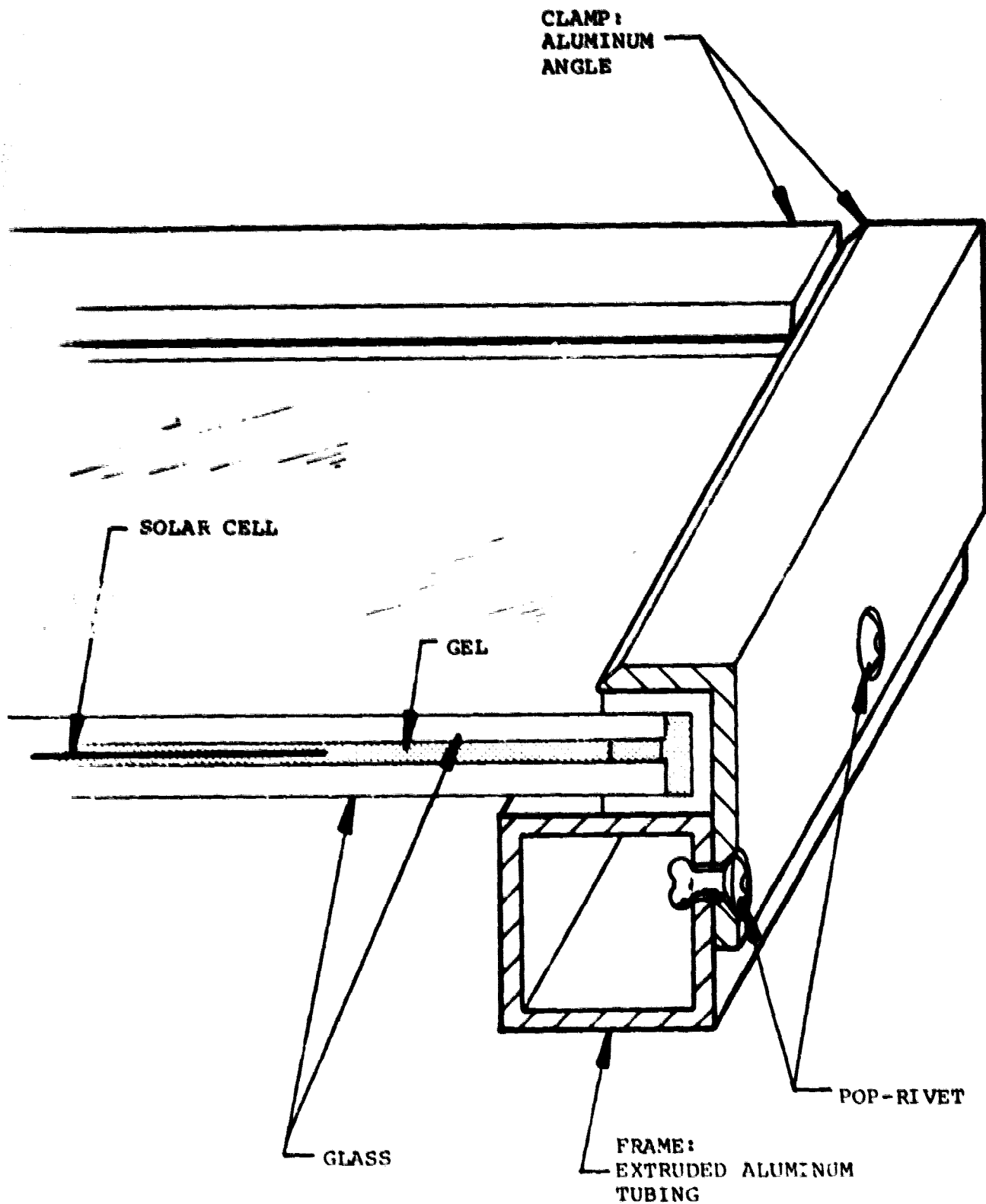


Figure 6. Mechanical Construction of Solar Cell Module

2.5 ELECTRICAL CONNECTIONS

All electrical interconnections within the modules are made with annealed, expanded, silver mesh ribbon. Silver was chosen for these units but solder coated copper mesh could be substituted. The mesh was attached with physically separated spots of solder (2% silver, 62% tin, and 36% lead) for redundancy.

The electrical output from the module is carried through a two terminal connector block passing through the back sheet of glass. It is set away from the grounded metal frame edge to achieve maximum electrical insulation. The terminals consist of two nickel plated, connected, threaded brass posts which pass through separate holes in the back glass sheet. This design prevents the possibility of post rotation and provides redundant output terminations. The exterior of the connector posts is covered by a thermosetting phenolic box to protect the external module interconnections from the environment, as is shown in the photograph of Figure 7.

2.6 THERMAL CONTROL

The module design carefully considered thermal performance. Except for the solar cells, the module is reflective white to reduce unnecessary solar radiation absorption. All of the external surfaces are characterized by high emissivity (glass 0.94 and white epoxy paint 0.89) for effective radiative cooling. In addition, the inside of the back glass sheet is painted with the white epoxy paint for thermal control and for cell current enhancement action.

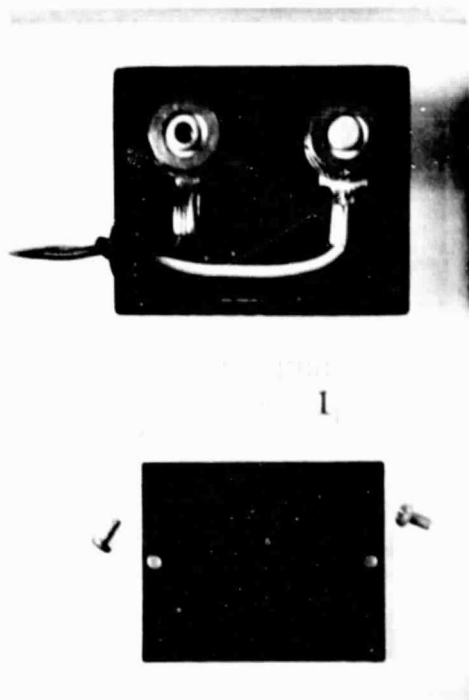


Figure 7. Solar Cell Module Terminal Box Assembly.

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SECTION III

MODULE PERFORMANCE

3.1 ELECTRICAL OUTPUT

The I-V characteristic of a typical module is shown in Figure 8. This, as well as other module data to be presented, was acquired using the AMI pulsed solar simulator facility at Solar Power Corporation, Billerica, MA. The I-V characteristic shows a short circuit current of 1.15 amps, an open circuit voltage of 27.3 volts, and a fill factor of 0.75. Overall efficiency of the 23 inch X 23 inch module is therefore 6.9%. Packing efficiency can be calculated to be 64% so that the effective cell efficiency is approximately 10.7%, AMI.

Table II summarizes the peak power outputs of the 12 modules at a test temperature of $24.5 \pm 1.5^{\circ}\text{C}$, before environmental testing. As will be discussed, module degradation after environmental testing was less than 8% at the maximum power point and less than 2% at 15.8 volts. The table shows that the total power delivered by the 12 modules is 278 watts or an average of 23.2 watts per module at the peak power point. The corresponding module average power output, at 15.8 volts and at 24.5°C is 18.1 watts.

Figure 9 shows the expected module performance versus cell temperature at the 15.8 volt level and maximum power point. This performance was determined by using data acquired from the AMO testing of individual bare cells as a function of temperature and scaling accordingly. The figure shows that power output at 15.8 volts is approximately constant over the operating temperature range of the module.

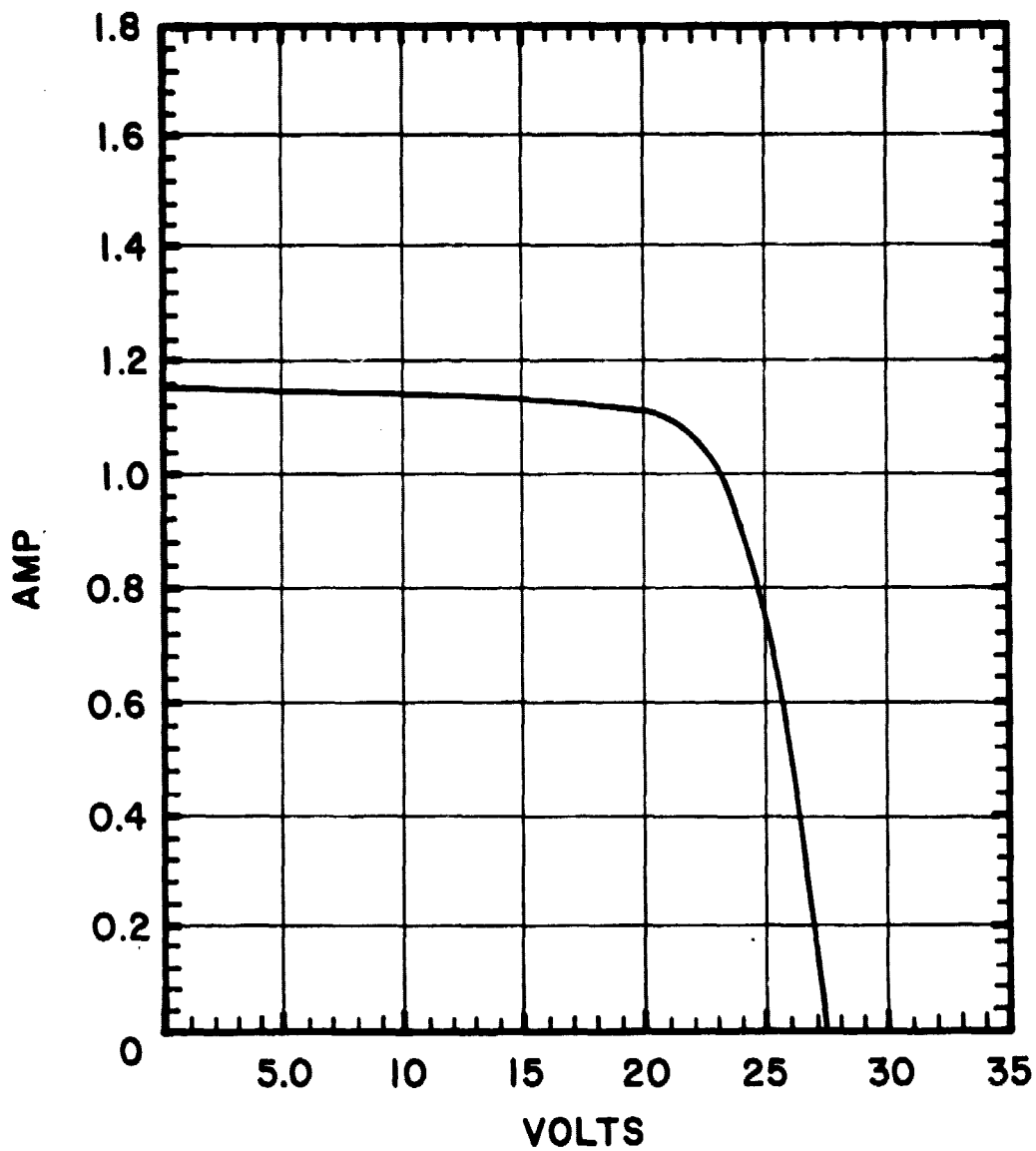


Figure 8. Representative AM1 I-V Characteristic
for Spire Module No. 67716C

TABLE II

SOLAR CELL MODULE MAXIMUM POWER OUTPUT AT
24.5°C, BEFORE ENVIRONMENTAL TESTING

MODULE NUMBER	IDENTIFICATION	P _{max} (WATTS)
1	17710A	22.1
2	47716C	22.7
3	57715B	22.2
4	67716C	23.4
5	77716C	24.5
6	87717C	25.0
7	97721B	23.4
8	107721B	22.8
9	117721B	23.1
10	127721B	23.1
11	137721B	23.1
12	147721B	22.9

Mean 23.2 watts/module

Standard Deviation $\pm$ 0.8 watts

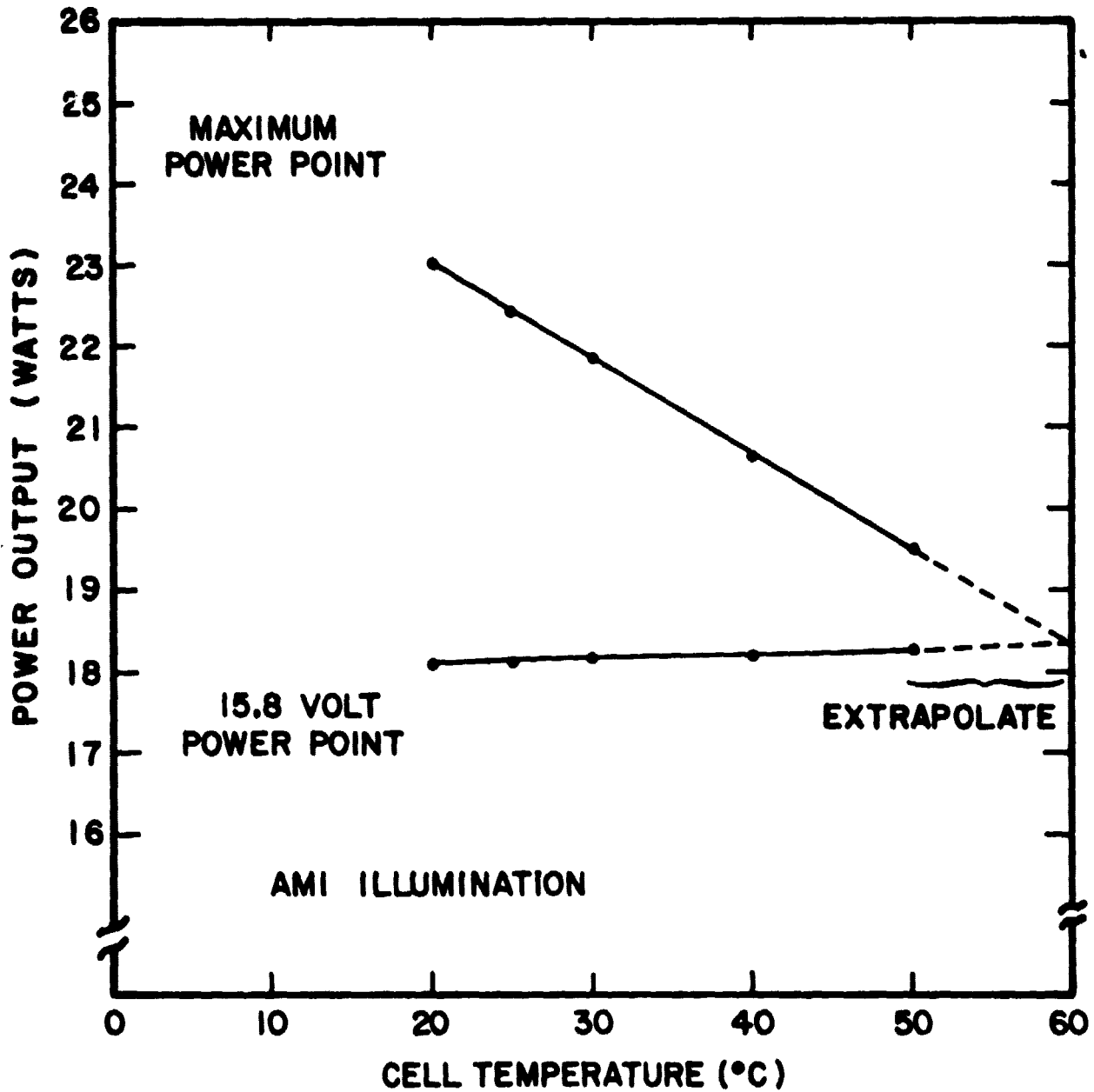


Figure 9. Module Power Output vs. Cell Temperature at 15.8 Volts and at Maximum Power Point

3.2 ENVIRONMENTAL TESTING

The major portion of the environmental testing was performed by the Acton Environmental Testing Laboratory, Acton, MA. Their test report, contained in Appendix A, describes their procedures for the thermal cycling, humidity, and mechanical loading tests.

The tests were as specified in JPL Specification 5-342-1, Revision B, and were conducted sequentially in the order summarized below. Module electrical performance tests and visual inspections were performed before and after each environmental test. Electrical isolation tests were performed before and after environmental testing.

Thermal Cycling

Each module was subjected to 50 cycles with the temperature varying between -40°C and $+90^{\circ}\text{C}$. Each cycle from room temperature to $+90^{\circ}\text{C}$ to -40°C to room temperature took six hours.

At the completion of this phase of testing, visual inspection revealed air bubble formation in the silicone gel. Also, although believed to be unrelated, the module average peak power dropped about 0.9 watts to 22.2 watts.

Humidity

The humidity tests were performed in a standard humidity-temperature chamber with procedures conforming to MIL-STD-810C. The humidity cycle was as specified and is contained in Appendix A.

No further bubble formation was visible at the completion of this test. The module average peak power dropped 0.2 watts to about 22.0 watts which is within experimental error.

Mechanical Integrity Tests

Each module was subjected to 100 cyclic mechanical loadings during which the module was supported only at the design support points. A water bag, weighing 187 pounds, was used to provide an even distribution of weight over the entire module surface. This corresponds to the 50 pounds per square foot test requirement. This weight was applied, cyclically, to the module front surface and then to the rear surface.

The visual inspection revealed no adverse module effects. No observable cracks or mechanical degradation occurred. The electrical test found an average module output of 22.8 watts, up 0.8 watts from the previous value, again within experimental error.

Table III summarizes module electrical performance data before and after environmental testing, both at 15.8 volt power level and at the maximum power point. The greatest degradation, observed for module 87717C, was about 7.2% at the maximum power point and 2% at 15.8 volts.

Electrical Insulation Tests

In addition to the Acton Laboratories environmental tests, Spire conducted the two types of electrical insulation tests required by JPL Specification 5-342-1, Revision B. The insulation resistance of six modules was measured and found to be well in excess of 100 megohms before the application of high voltage, after one minute of +1000VDC, and after one minute of -1000VDC.

TABLE III

SPIRE CELL MODULE POWER OUTPUT AT MAXIMUM POWER POINT
AND AT 15.8 VOLTS FOR 24.5°C BEFORE AND AFTER ENVIRONMENTAL TESTING

MODULE I.D. NO.	INITIAL P _{15.8 V} (WATTS)	FINAL P _{15.8 V} (WATTS)	DEGRADATION AT 15.8 V (%)	INITIAL P _{max} (WATTS)	FINAL P _{max} (WATTS)	DEGRADATION AT MAX. (%)
17710A	17.9	18.0	+0.5	22.1	22.9	+3.6
47716C	18.3	18.2	0.0	22.7	23.0	+1.3
57715B	18.1	17.9	-1.0	22.2	22.0	-0.9
67716C	17.8	17.5	-1.6	23.4	21.9	-6.4
77716C	18.5	18.3	-1.0	24.5	23.8	-2.8
87717C	18.9	18.5	-2.0	25.0	23.2	-7.2
97721B	18.2			23.4		
107721B	18.1			22.8		
117721B	17.8	To be tested by JPL.		23.1	To be tested by JPL	
127721B	17.7			23.1		
137721B	17.9			23.2		
147721B	17.5			22.9		
Average	18.1			23.2		

The results of these voltage withstanding tests are given in Table IV. No evidence of dielectric breakdown or voltage interruption was observed. Minor increases observed in leakage currents after environmental testing were due, in part, to contamination on the module surface. These results indicate the additional operational safety provided by the glass laminate design.

TABLE IV

VOLTAGE WITHSTANDING TEST DATA SUMMARY

APPLIED VOLTAGE = 500 V V = 1000 V V = 1500 V
 TIME = 15 SECONDS T = 15 SEC. T = 60 SEC.

MODULE IDENTIFICATION NUMBER	INITIAL LEAKAGE CURRENT (nA)	FINAL LEAKAGE CURRENT (nA)	INITIAL LEAKAGE CURRENT (nA)	FINAL LEAKAGE CURRENT (nA)	INITIAL LEAKAGE CURRENT (nA)	FINAL LEAKAGE CURRENT (nA)
17710A	5	45	12	80	15	125
47716C	4	30	6	70	10	100
57715B	8	40	11	70	11	85
67716C	7	30	7	65	7	80
77716C	4	30	9	60	9	85
87717C	24	50	24	150	24	200

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SECTION IV

MODULE DESIGN PROBLEMS

The principal problem encountered, as a result of the environmental tests, was the occurrence of air bubbles in the silicone gel encapsulant. Although three gasket design configurations were evaluated during the course of the program, none was able to provide adequate air sealing for even moderate thermal cycling because of the high volume coefficient of thermal expansion of the gel. Even though substantial volume change is accommodated by glass flexing, it is still not sufficient to prevent air from being introduced through the perimeter gasket.

No degradation in module performances could, however, be attributed to bubble formation so that it appears that the problem is limited to being a cosmetic defect.

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SECTION V

SUBSEQUENT DESIGN MODIFICATIONS

After delivery of the twelve modules required by contract to JPL, Spire continued gasket development. A polysulfide rubber gasket was formed in place by drawing a bead of material around the glass periphery and clamping the glass sheets together. After curing, silicone gel was introduced into the cavity. This design was found to prevent bubble formation. Fifty thermal cycles between -10°C and $+90^{\circ}\text{C}$ resulted in no bubble formation in several test modules.

Two modules were filled with the gel within eight hours of gasket formation, while four modules were filled after a ten day cure. After eight months of environmental testing on the roof of Spire's Bedford, MA. facility, discoloration of the silicone gel near the module frame is occurring in the gaskets cured for eight hours but not in those cured for ten days. It may be that the polysulfide was not sufficiently cured in eight hours and is diffusing through the silicone gel. The effect of this discoloration upon module electrical performance has not been assessed. No other degradation mechanism is apparent from these tests to date.

A second design modification also was implemented after JPL module delivery. The utilization of the wet polysulfide gasket allowed passing four expanded silver interconnect strips through the gasket out of the module. Two standard weatherproof automotive connectors were then soldered to these strips and wrapped in Mylar. This design results in cost savings, a more interchangeable module, and has shown superior high voltage insulating characteristics.

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SECTION VI

SUMMARY

This program achieved its objective of producing 12 solar cell modules utilizing ion implanted solar cells and an all-glass encapsulation system. These modules have exhibited only cosmetic degradation after environmental testing.

The principal problem encountered was the formation of bubbles in the silicone gel due to gasket air leakage during thermal cycling. Developmental effort, after delivery of the modules to JPL, indicates that this can be rectified by the use of a polysulfide gasket.

Significant improvements in the module design that can be recognized are the use of tempered, low iron content glass for increased module output, and the substitution of a custom aluminum extrusion for reduced weight and increased rigidity.

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APPENDIX A

Test Report No. 13118

No. of Pages 5

Report of Test on

SOLAR CELL MODULES
FOR SIMULATION PHYSICS, INC./RESEARCH
UNDER PURCHASE ORDER NO. 62320



Date June 8, 1977

	Prepared	Checked	Approved
By	W. Schreiner	A. Dentino	M. L. Tolf
Signed	<i>W. Schreiner</i>	<i>A. Dentino</i>	<i>M. L. Tolf</i>
Date	<i>6/8/77</i>	<i>6/8/77</i>	<i>6/8/77</i>

WJS/hmf

Administrative Data

- 1.0 Purpose of Test:** To ascertain that the Solar Cell Modules withstand the environments as described herein.
- 2.0 Manufacturer:** Simulation Physics, Inc./Research
- 3.0 Manufacturer's Type or Model No:** Solar Cell Modules
- 4.0 Drawing, Specification or Exhibit:** Modular Environmental Tests Specification 5-342-1 Rev B
- 5.0 Quantity of Items Tested:** Six (6) of the above type
S/Ns 87717C, 17710A, 57715B,
77716C, 67716C & 47716C
- 6.0 Security Classification of Items:** None
- 7.0 Date Test Completed:** May 31, 1977
- 8.0 Test Conducted By:** A.Dentino
R.Labrecque
- 9.0 Disposition of Specimens:** Returned to Simulation Physics,
Inc./Research.
- 10.0 Abstract:** Refer to result sections herein.

Report No. 13118

Page 1



1.0 REQUIREMENTS, PROCEDURES & RESULTS

1.1 THERMAL CYCLING

Requirements

Each module shall be subjected to 50 cycles with the cell temperature varying between -40°C and $+90^{\circ}\text{C}$. The temperature shall vary approximately linearly with time at a rate not exceeding $100^{\circ}\text{C}/\text{hour}$ and with a period not greater than 6 hours/cycle.

Procedures

The test samples were placed within a Conrad High-Low Temperature Chamber. The test chamber was controlled so that each cycle from room to -40°C increased to $+90^{\circ}\text{C}$ and returned to room was 6 hours. The test samples were subjected to 50 of the above cycles.

At the end of 8 cycles and again at 12 cycles, Simulation Physics personnel removed the test samples from the chamber and visually examined the items.

Upon completion of the 50 cycles, the test samples were removed from the chamber and visually examined for evidence of any physical damage and returned to Simulation Physics for electrical measurements.

Results

There was some evidence of bubbling behind the glass noted. Simulation Physics personnel retained data.

Report No. 13118

1.2 HUMIDITY

Requirements

Each module shall be subjected to the humidity cycling procedure as shown in Figure 1 herein.

Procedures

The test samples were placed within a Tenney Eng. Temperature/Humidity Chamber, Model TH-27. The test samples were then exposed to the humidity cycling test as shown in Figure 1 of this report.

Following exposure to this humidity test, the samples were removed from the chamber and visually examined for evidence of any physical damage and Simulation Physics personnel returned the samples to their plant and performed electrical measurements.

Results

There was no evidence of any physical damage as a result of this environment.

Report No. 13118

1.3 MECHANICAL INTEGRITY TEST

Requirements

Each module shall be subjected to a cyclic load test in which the module is supported only at the design support points by a rigid fixture and a uniform load normal to the modular surface is cycled from +50 lbs/sq. foot to -50 lbs/sq.foot 100 times.

Procedures

Each module was subjected to the cyclic load test as specified in the requirements above. The weight used was 187 lbs of water which would produce an even distribution of weight over the surface.

The test was performed manually by placing the weight on one side of the panel and lifting the weight, turning the panel over and again placing the weight on the other side. This constituted one cycle.

The test samples were subjected to 100 of such cycles.

Upon completion of this mechanical integrity test, the samples were visually examined for evidence of any physical damage.

Results

There was no evidence of any physical damage as a result of this environment.

Report No. 13118

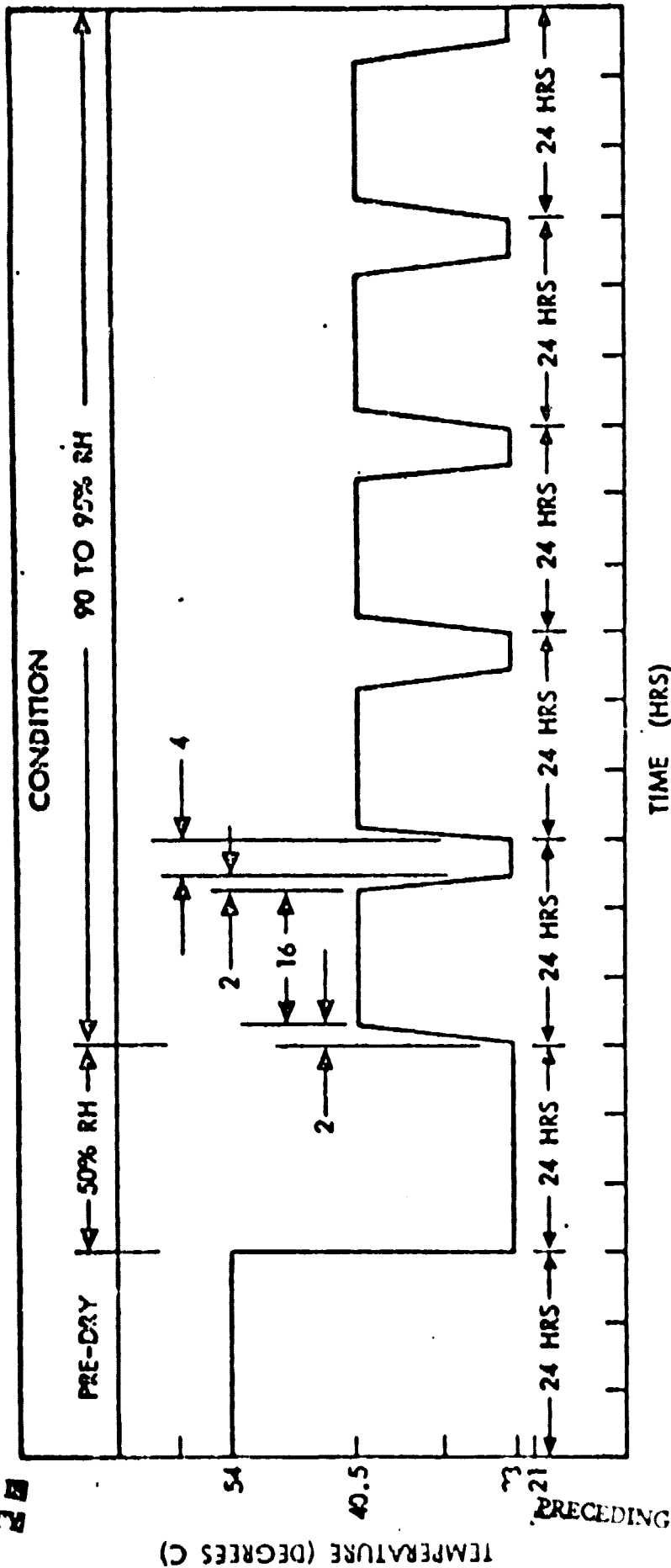


Figure 1 Humidity Cycle Test (Suitable procedures for accomplishing this test are described in MIL-STD-810C, Method 507.1, Procedure V.)